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Working paper on problems in determining the body wave magnitude

1. Present importance of body wave magnitude mb in CTB issue

The United Kingdom Working Paper CCD/363 gave a pertinent summary on seismic magnitudes with special reference to CTB discussion. As described there, we have used from the beginning in CTB issues seismic magnitude in terms of mb, body wave magnitude determined by short-period vertical component seismometers almost exclusively. Only recently has the adequacy of applying Ms instead of mb been pointed out and Ms is recommended as representing the equivalent yield better than mb in the Swedish, Canadian and United Kingdom Working Papers (CCD/306, CCD/327 and CCD/363).

However, it must be noted that the above results have been mainly obtained on a research basis and the seismological routine service determines Ms only for a several per cent of all detected seismic events of the globe, but mb for almost all of them. The detection capabilities of the present routine network for surface waves is presently much lower than that for P waves, although the deployment of a high-gain-long-period seismograph network will be able to improve the level. As in CTB the detection and identification of small size events are important, we cannot at least for the moment switch over from mb to Ms to represent the size. Moreover a sudden employment of Ms in place of mb will also confuse people who have been accustomed to use the mb scale for a long time in the CTB issues and it may be premature to switch over from mb to Ms. Also, considering the importance of discrimination by mb:Ms method and some promising short period discriminants, we cannot live without mb. Thus, we should try to obtain the undisputable agreed value of mb for all events in our routine monitoring system for CTB.

2. Fluctuation of body wave magnitude

In CCD/363 the anomalous values of mb at Eskdalemuir Array in Scotland (EKA)^{*/} for the two United States nuclear explosions, Gasbuggy and Rulison, relative to their yield in kT are described. Namely, mb at EKA is 5.4 for 26 kT Gasbuggy, while mb at

^{*/} All seismographic stations have their own three letter abbreviations which are found in "Seismograph Station Abbreviations and Co-ordinates" published by NOAA, United States Department of Commerce or in "Regional Catalogue of Earthquakes" published half-yearly by I.S.C., Edinburgh.

EMA for 40kT Rulison is only 4.7. The CCD/365 gave teleseismic average values of mb for Gasbuggy and Rulison as 5.0 and 4.9 respectively, with less discrepancy in the yields. The bulletin of ISC gives mb 4.8 on 14 observations for Gasbuggy and mb 5.0 on 17 observations for Rulison. The relation between yield and mb looks more reasonable. Another example showing more anomalous relations between yield and mb in CCD/365 are large Soviet chemical explosions Nedao (1) and (2), 1.7 MT and 5.6 MT giving mb 5.0 and 5.2 at EMA respectively. The mb values are too large compared with that of Rulison and Gasbuggy.

It is commonly thought that, although mb at individual stations differs from station to station, their average gives a stable mb with standard deviation less than $\frac{1}{4}$ if we take mb at more than 20-30 stations. An individual station mb would very probably show inevitable fluctuations and cannot be considered as a reliable measure of the size of events. If one party uses the mean value of mb obtained at a few arbitrary stations, it is very probable that other parties would not agree about the value and consequently any conclusion derived by using that particular mb cannot be accepted. In the following section an example of such a disagreement will be given.

3. On Tibet-Assam explosion-like seismic events with special reference to their mb values

United States Working Paper CCD/388 was very important and instructive for our CTE issues. It has a constructive side in reviewing recent technical accomplishments which give us ideas of detecting and identifying teleseismic events down to mb 4.0, while in 1960 we considered mb 4.75 a remote target. The several remaining problems mentioned are, of course, all very important and in particular it is to be welcomed that the paper pointed out explicitly the problem of anomalous events, showing concrete examples, which had often been mentioned vaguely against the optimistic opinion on discrimination. For the problems of mixed events and of the rate of doubtful events in the USSR, it is hoped to give a concrete presentation as for the Tibet-Assam anomalous events which will make possible follow-up examinations and further studies by other parties.

As CCD/388 noted, the existence of anomalous explosion-like earthquakes is very serious and the problem should be investigated carefully. Our examination will be described in the following.

CCD/388 investigated 53 Tibet-Assam shallow seismic events during 1963-1970, of which 50 are listed in its Table IV. Although we feel uneasiness about the accuracy of M_s determination based on stations within narrow range of distance and azimuth from the foci, we did not examine M_s and only re-examined the m_b values from the published data source in order to check the anomalous events on the $m_b:M_s$ diagram in Fig.5 of CCD/388. We reproduce here the list partly with numbers in chronological order for each event in Table 1. Table 1 shows where each event falls either in the earthquake-like (I), intermediate (II) or explosion-like (III) regions in the $m_b:M_s$ diagram adopted in CCD/388. We listed in Table 1 also the mean m_b of USCGS (NOAA since July, 1970) and ISC with the number of observations (or stations) used. ISC does not give mean m_b when m_b is reported by a very few stations, and for such events the m_b of individual station with station distance in degrees is given in Table 1 in parentheses.

The left figure of Fig.1 (1A) is a reproduction of Fig.5 in CCD/388 giving order number to be referred to that in Table 1 for the convenience of identifying the events. CCD/388 pointed out two anomalous events above m_b 5.0 which lie in the Basham-Marshall explosion region hatched in the $m_b:M_s$ diagram in this figure. They are No.12 (8.1, 1965) and No.46 (8.15, 1969). There are three other events in the explosion-like region (Region III) with $m_b = 5.0$, i.e. No.32 (7.13, 1968), No.40 (8.25, 1968) and No.41 (8.29, 1968). CCD/388 takes m_b probably from PDE or EDA of NOAA. For several events m_b adopted by CCD/388 and mean m_b of USCGS given in Bull. ISC are slightly different as indicated by * marks in Table 1. (Nos. 9, 10, 13, 16, 17, 18, 19, 20, 21, 24). Except Nos. 9 and 10, the mean m_b 's given in Bull. ISC are 0.1-0.2 smaller than m_b adopted by CCD/388, which moves the points in $m_b:M_s$ diagram in the direction of the earthquake-like region.

The number of observations used to calculate the mean m_b can be taken as a measure of the reliability of the m_b value. m_b of the anomalous event No.12 seems to be based on m_b at SHL (India, $\Delta = 7^\circ$)* alone. In Bull. ISC we also found m_b 4.9 at EKA (Scotland, $\Delta = 67^\circ$), beside m_b 5.5 at SHL of Δ of only 7° . To adopt the m_b value at near stations is generally questioned and ISC excludes as a rule m_b at

* / Δ means epicentral distance.

stations $\Delta < 21^\circ$ in the calculation of mean mb. Thus we have to consider that the mb 5.5 of event No.12 is of poor reliability. The simple mean of two mb's at SHL and EKA is 5.2 but more weight should be given to EKA of a greater epicentral distance. Anyway the mb of this event must be much smaller than 5.5, shifting the position in the mb:Ms diagram certainly well outside the explosion-like region.

In Fig.2 the number of reported P arrival times and mb values in the Bull. ISC are shown. In the figure the number of P reports of event No.12 of mb 5.2 seems too few compared with other events of the same magnitude. It suggests that even mb 5.2 for No.12 is too large. Thus we cannot agree that this event should be accepted as an example of explosion-like anomalous events.

The mb 5.2 of another anomalous event No.46 is the mean of four stations as shown in Table 2, namely mb 5.0 at GIL (Alaska, $\Delta = 74^\circ$), mb 5.1 at FMR (Alaska, $\Delta = 75^\circ$) and mb 5.7 at BNG (Republic of Central Africa, $\Delta = 76^\circ$) and mb 5.0 at BUL (Rhodesia, $\Delta = 81^\circ$). The mean seems strongly affected by the value at BNG, and a recent investigation by Miyamura, 1972 (Appendix)^{*/} shows that the station correction to be added to the mb at BNG for central Asian events is -0.15 ± 0.29 . It is noticed that the standard deviation of mb variations at BNG is rather large at ± 0.29 . As listed in Table 1, the ISC mean mb for this event is mb 4.9 from 9 observations and according to the above consideration mb 5.2 for this event seems to be somewhat large. Fig.2 indicates that the ISC mean mb 4.9 is reasonable in relation to the number of P reports. Thus we can move this event at least from the explosion-like region to the intermediate region in the mb:Ms diagram by changing mb from 5.2 to 4.9.

Three explosion-like events, Nos. 32, 40 and 41 with mb 5.0 or less are near the border of regions II and III on mb:Ms diagram in Fig.1A and their mb's are based on 4-5 stations as shown in Table 2. ISC mean values based on larger number of observations for them are 0.1-0.2 smaller than USCGS (NOAA) mean values and these events will move from the explosion-like region into the intermediate region.

As Table 1 shows, the mb values of USCGS (NOAA) which CCD/388 adopted, are generally based on fewer observations than the ISC mean. Furthermore ISC excludes near and regional stations to reject effects of regional inhomogeneity of the upper mantle structure on mb values and also the data are obtained in principle by re-examined interpretations. Accordingly, it is reasonable to think that ISC mb is a

^{*/} Appendix is available at the Secretariat of CCD.

better estimate of mb than NOAA mb which is rather preliminary. Adopting ISC mean mb's and Ms's of CCD/388, we constructed mb:Ms diagram as shown in Fig. 1B. This latter diagram shows no point in the explosion-like region (Region III) for all magnitude ranges. There remain many events of mb less than 5.0 in the intermediate region (Region II), but no event with $mb \geq 5.0$ is even in the intermediate region. The Tibet-Assam shallow seismic events are thus considered to be all normal earthquake-like events at least for mb not less than 5.0 and they are clearly separated from explosion-like as well as from the intermediate region in the mb:Ms diagram, when we adopt ISC mean mb. We cannot deny that many events with mb less than 5 are in the intermediate region. However, it is still open for discussion whether we could extend the explosion-like region bounded by $Ms = 0.5$ $mb - 1.5$ to the unhatched region of mb less than 5.

Anyway, we have reached a somewhat different conclusion on the Tibet-Assam "anomalous" events and this new interpretation arises only from the mb values adopted. It indicates that the determination of mb on a more appropriate basis is necessary to apply mb:Ms method of discrimination for CTB. For the discussion of the threshold of verification, an agreement on mb value for each seismic event is also necessary.

Although it is very difficult to approach the true value of mb, the urgent need is to reach an agreement on the determination of mb, namely, by what method and on what data. We made some preparatory work to select reliable stations for the mb determination in the existing international seismological routine in order to provide a practical basis for this problem.

4. Selection of reliable stations for the routine determination of body wave magnitude for CTB

More than 500 seismological stations in different countries of the world are now co-operating in the routine rapid service of Preliminary Determination of Epicenters (PDE) of National Oceanic and Atmospheric Administration (NOAA) of United States Department of Commerce in sending their seismometric interpretations by telegram or by air-mail every day or every week. The collected data are used to calculate the epicenter co-ordinates, focal depths and magnitudes by computer and the results are printed and distributed as PDE after a couple of months to the contributing stations, interested institutes and individual scientists of the world. All data used in PDE are also published as Earthquake Data Reports (EDR) subsequently. The seismic events of the world are now routinely detected and located by this rapid service and when we discuss the detection and identification of underground nuclear explosions, it is indispensable to be well acquainted with the present state of this service in order to investigate a practically feasible seismic verification system for CTB.

As reviewed in CCD/363 short-period body wave magnitudes have been systematically determined in PDE service for almost all seismic events located and have now become a useful measure of the size of event down to the smallest detectable earthquakes. However, as described in the previous sections with reference to United Kingdom and United States Working Papers, fluctuation of mb is very critical in relation to the seismological verification for explosions. It is necessary to avoid argument about the adopted magnitude values among the parties when the estimation of event size or discrimination needs the magnitude values. Especially, when the mb differs from station to station very much for a certain event and consequently different mean mb's are obtained for different combination of stations, we need to have a mutually agreed magnitude value.

For the routine monitoring of earthquakes, PDE service seems to be the only workable basis at present and we investigated the actual state of the mb determination of PDE. The details of the investigation can be found in the paper of Miyamura, 1972 given as Appendix. Station biases of mb for different stations are obtained for the NTS and E. Kazakh explosions separately.

As is shown in Appendix, reliable teleseismic stations for mb determination are as follows:

1. for NTS: GPO (USA); PMR, COL, GIL (Alaska); LPS (El Salvador); MBC, NP-, ALE (Canada); SJG (Puerto Rico); CAR (Venezuela); KTG (Greenland); LFB (Bolivia); KJN, NUR (Finland); TSK (Japan); BNS, GRF, FUR (FRG); MOX, CLL (GDR)
2. for E. Kazakh: NDI, SHL, POO, HYB (India); NUR, KJN, KEV (Finland); COP (Denmark); CLL, MOX (GDR); GRF, FUR, STU, BNS (FRG); NOR, KTG (Greenland); TSK, OIS (Japan); GIL, COL, PMR (Alaska); NP-, MBC, INK, CMC, FBC, GWC, FSJ, EIM, PNT (Canada); BNG (Republic of Central Africa); BUL (Rhodesia); PRE (South Africa); NEW, LON, LF4, LAO, BOZ, BMO, DUG, UBO, EUR, GOL, BKS, CPO, ALQ, WMO, TFO (USA); MUN, PMG (Australia).

Comparing the total number of stations reporting P arrival times to NOAA, the number of the above stations seems to be very small and in reality quite insufficient for reliable mb determination.

There are many other sensitive stations such as UPP, KIR, UME, HFS (Sweden), SOD (Finland), KHC, PRU (Czechoslovakia), MAT, DDR (Japan), YKC (Canada), WRA, ASP (Australia), SPA (Antarctica), etc. which have certainly a potentiality for reporting mb data but have not been sending them to NOAA. For example, MAT has begun reporting mb recently with fair reliability. We can include some of them and invite many others to report regularly not only P arrival times but also mb data to NOAA.

It is quite regrettable that some of the above-mentioned reliable stations such as WMO and TFO discontinued their reports to NOAA recently. Geographically uneven distribution of reliable stations for mb determination is clearly observed as shown in Figs. 11 and 12 of Appendix with respect to the epicenters and more reports from the vast blank areas of Asia, Africa and South America are especially needed.

In order to select key stations for the mb determination of seismic events in the different parts of the world, the present investigation suggests that the urgent need is to increase the reporting stations. To begin with, we have to use the above selected stations plus several reliable sensitive stations such as MAT, HFS, YKO, etc.

A rapid seismological routine service based on many stations in many different parts of the world like PDE service is indispensable to the verification for CTB. Monitoring only by a small number of array stations may not be sufficient to secure unbiased mb values of seismic events in various parts of the world, though this problem has not yet been fully examined.

Table 1

NO.	CCD/388			TIME		MAG.		REGION	USCGS	PDE NO.	ISC
	DATE					mb	Ms		mb/NO. OF OBS. (SAT.)		mb/NO. OF OBS. (STA. Δ)
	M	D	Y	H	M						
1	07	05	63	07	12	4.2	3.90	I			
2	10	08	63	02	51	5.4	4.33	II			
3	11	16	63	11	39	4.7	3.93	I			
4	01	07	64	04	50	5.0	4.38	I	5.0/COL		(5.0/COL, 72°)
5	01	27	64	05	29	4.9	3.87	II	4.9/COL		(5.4/COL, 74°)
6	04	30	65	07	13	4.4	3.96	I	4.4/COL		(4.5/COL, 75°)
7	06	04	65	15	56	5.0	3.87	II	5.0/2		(5.3/SHL, 7°, 4.8/COL, 72°)
8	07	31	65	16	36	4.9	4.27	I	4.9/2		4.8/3
9	07	31	65	17	07	4.7*	4.81	I	4.8/4		5.0/7
10	07	31	65	19	01	4.4*	4.40	I	4.7/4		4.8/8
11	07	31	65	21	44	4.9	4.60	I	4.9/4		5.0/9
12	08	01	65	14	14	5.5	3.94	III	5.5/SHL, 7°	67	(5.5/SHL, 7° 4.9/EKA, 67°)
13	08	01	65	20	09	5.3*	4.78	I	5.2/8	63	5.2/15
14	08	02	65	17	49	4.8	4.35	I	4.8/4	71	4.7/4
15	10	06	65	08	03	5.4	4.19	II	5.4/3	79	4.9/4
16	12	09	65	20	26	5.3*	4.47	I	5.1/3	44	5.0/6
17	01	31	66	02	35	5.6*	4.87	I	5.4/12	6	5.1/18
18	03	14	66	04	42	4.9*	4.46	I	4.8/7	17	4.8/10
19	05	27	66	14	35	4.8*	4.34	I	4.7/6	36	4.7/8
20	09	11	66	15	55	5.0*	3.77	II	4.8/STU, BUL	67	4.7/5
21	09	26	66	05	10	5.6*	5.26	I	5.5/14	67	5.4/25
22	09	36	66	06	03	4.2	3.59	I	4.2/POO, 20°	74	(4.1/POO, 19°)
23	03	11	67	16	56	5.3	4.69	I	5.3/12	19	5.1/20
24	03	14	67	06	58	5.9*	5.54	I	5.8/16	16	5.7/32
25	07	07	67	22	56	4.9	3.71	II	4.9/STU, COL	47	4.8/5

Table 1 (cont'd)

26	08	15	67	09	21	5.7	5.07	I	5.7/15	55	5.5/28
27	02	16	68	05	37	4.8	4.51	I	4.8/6	11	4.7/9
28	06	28	68	20	34	4.8	3.58	II	4.8/3	48	4.8/8
29	06	30	68	05	04	4.8	3.40	II	4.8/3	54	4.7/6
30	07	01	68	03	11	4.3	3.00	II	4.3/BUL, 81°	53	4.0/4
31	07	04	68	06	45	4.7	3.46	II	4.7/3	48	4.7/11
32	07	13	68	06	05	5.0	3.46	III	5.0/5	56	4.8/9
33	07	14	68	18	12	4.9	3.54	II	4.9/6	54	4.8/12
34	07	15	68	05	09	4.8	3.39	II	4.8/COL, 73°	60	4.7/6
35	07	16	68	22	23	4.8	3.45	II	4.8/4	54	4.6/8
36	07	23	68	20	51	4.9	3.43	II	4.9/4	59	4.8/10
37	07	26	68	12	44	4.9	3.45	II	4.9/5	61	4.7/9
38	08	23	68	12	01	4.8	3.46	II	4.8/4	64	4.7/10
39	08	24	68	14	26	4.6	3.35	II	4.6/SHL, COL	68	4.8/5
40	08	25	68	17	55	4.8	3.28	III	4.8/4	64	4.7/5
41	08	29	68	19	51	5.0	3.48	III	5.0/4	67	4.9/9
42	09	01	68	05	59	5.0	3.59	II	5.0/5	72	4.8/9
43	09	03	68	17	45	4.9	3.43	II	4.9/3	68	4.8/12
44	09	04	68	01	40	4.8	4.05	I	4.8/COL, 70°	70	(4.9/COL, 72°)
45	09	11	68	03	07	4.3	3.52	I	4.3/BNG, 76°	72	4.7/7
46	08	15	69	07	15	5.2	3.57	III	5.2/4	55	4.9/9
47	11	24	69	02	01	4.6	4.00	I	4.6/5	77	4.6/8
48	02	08	70	19	07	4.5	4.05	I	4.5/4	15	4.5/6
49	05	08	70	11	08	4.5	3.55	I	4.5/KJN, NP-	33	
50	06	24	70	00	34	4.8	4.53	I	4.8/8	45	

Table 2

EVENT	EDR 55-68		mb	STA.	DIST.	BULL		ISC STA.	DIST.	mb
	SAT.	DIST.				mb				
No. 12	SHL	7.2	5.5	SHL	7.2	5.5	EKA	67.5	4.9	
	mb on 1 obs.		5.5	no ISC mean is given						
No. 32	NP-	71.6	4.9	KJN	53.1	5.1	BNG	75.9	5.1	
	COL	73.5	4.8	MOX	63.1	4.9	KRR	78.3	4.8	
	ENG	75.8	5.0	FUR	64.0	5.2	BUL	81.0	4.8	
	BUL	80.9	4.9	NP-	71.5	5.0	mb on 9 obs.		4.8	
	mb on 4 obs.		5.0*	COL	73.5	5.0				
				CLK	73.5	4.9				
No. 40	SHL	5.4	4.9	SHL	5.4	4.9	BUL	81.0	4.8	
	GIL	73.5	4.7	PRU	61.4	4.8	mb on 5 obs.			
	PMR	74.9	4.7	GIL	73.5	4.8	excluding			
	BUL	81.1	4.8	PMR	74.9	4.7	SHL		4.7	
	mb on 4 obs.		4.8	BHA	77.8	4.8				
No. 41	NUR	54.6	5.3	NUR	34.6	5.3	PMR	75.0	5.0	
	COL	73.4	4.9	PRU	61.6	5.0	BHA	77.8	4.9	
	PMR	74.9	5.0	KON	62.1	5.3	CIR	79.4	4.7	
	BUL	81.2	4.6	CLK	73.5	5.0	BUL	81.0	4.7	
	mb on 4 obs.		5.0	COL	73.5	4.9	mb on 9 obs.		4.9	
No. 46	GIL	73.5	5.0	KHN	53.1	4.9	BNG	75.8	5.8	
	PMR	75.0	5.1	MOX	63.0	5.0	KRR	78.2	4.6	
	BNG	76.1	5.7	FUR	63.9	5.1	CIR	79.3	4.5	
	BUL	81.1	5.0	GIL	73.6	5.0	BUL	80.9	4.7	
	mb on 4 obs.		5.2	PMR	75.0	5.1	mb on 9 obs.		4.9	

Captions for Tables and Figures

Table 1. Tibet-Assam shallow earthquakes investigated in CCD/388 as including explosion-like seismic events. mb adopted in CCD/388 is slightly different from mb given in Bull. ISC.

Table 2. Station mb in EDR for Tibet-Assam events suspected as explosion-like in CCD/388.

*Arithmetic mean is 4.94.

Fig. 1. mb: Ms diagrams of Tibet-Assam shallow earthquakes investigated in CCD/388 as an example of population including explosion-like seismic events. 1A is mb: Ms diagram same as in Fig. 5 of CCD/388. Numbers attached to the points are the chronological order of numbers given in Table 1. 1B is mb: Ms diagram, taking ISC mean mb instead of mb adopted by CCD/388 from USCGS (NOAA).

I, II and III are earthquake-like, intermediate and explosion-like regions in the mb: Ms diagram adopted by CCD/388 and the hatched part is explosion domain by Basham-Marshall, 1972.

Fig. 2. The relation of the number of P arrival time reports N and mean mb by ISC

FIG. 1. mb : MS DIAGRAM FOR TIBET-ASSAM SHALLOW SEISMIC EVENTS

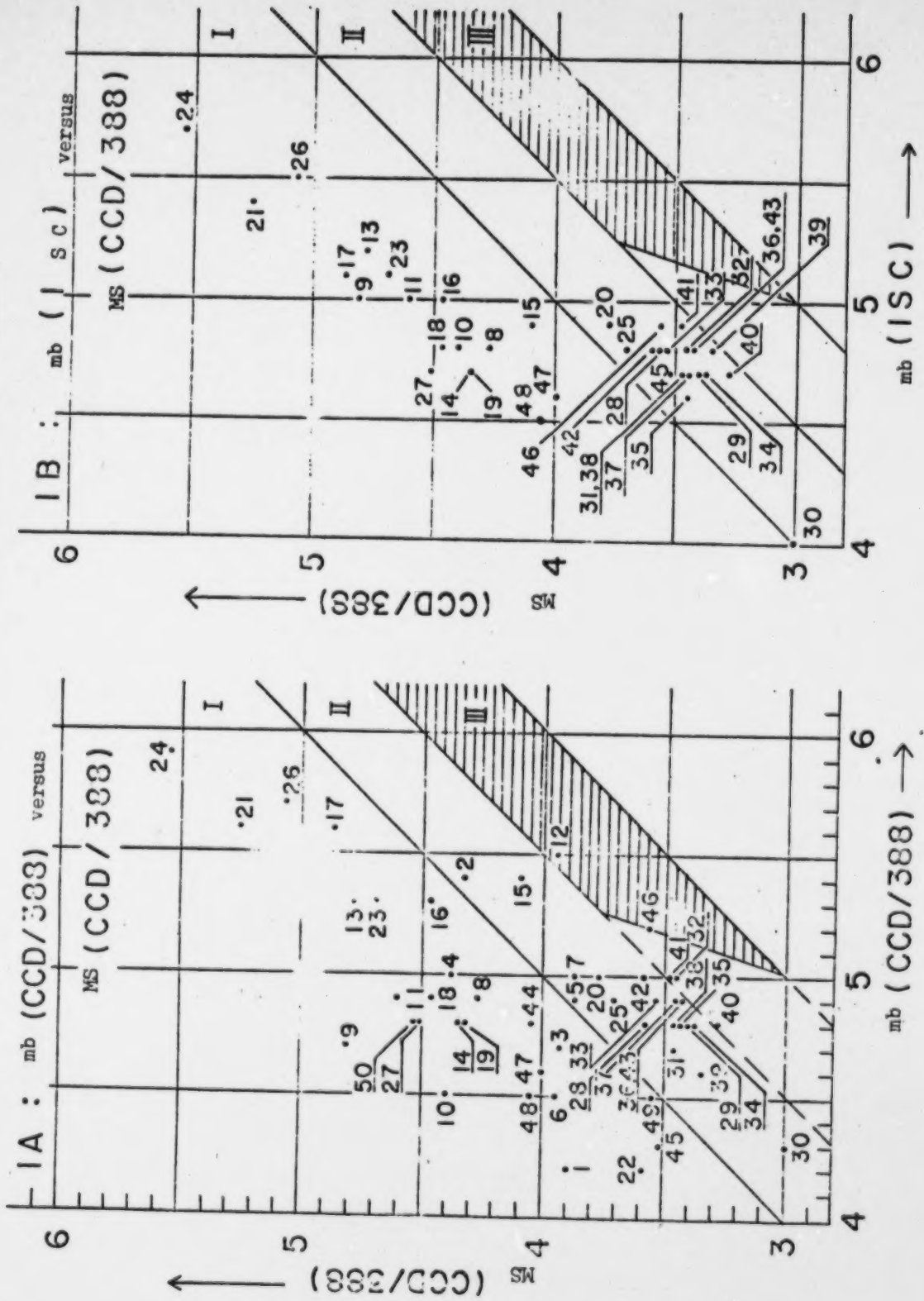


FIG. 2. NUMBER OF P REPORT AND mb OF
TIBET-ASSAM SHALLOW SEISMIC EVENTS

